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Living Seawalls for Tumbes: A Staged, Instrument-Based Protocol for Mangrove-Based Residential Coastal Protection in Peru

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Article

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Abstract

Background.

Nature-based solutions, and fringing mangroves in particular, are increasingly proposed as complements to conventional gray infrastructure for protecting coastal residential housing from storm surge and wind-wave action. The engineering literature that links mangrove structure to quantifiable, design-relevant parameters (wave-height attenuation coefficients, force reduction on foundations, monetized flood-damage avoidance) is well developed for the United States coastline, but is rarely translated into a stepwise, instrument-level protocol that a municipal or regional engineering office in a developing coastal region could actually execute.

Objective.

To synthesize peer-reviewed, DOI-verifiable evidence quantifying the protective value of fringing mangroves for residential structures during storm events, to translate that evidence into standard coastal-engineering formulas, and — as the central contribution of this paper — to convert that evidence into a staged, instrument- and materials-specific implementation protocol calibrated to the geomorphology, hydro-climatic regime, and institutional structure of Peru's northern coast (Tumbes region).

Methods.

A structured narrative synthesis (PRISMA-informed screening of the coastal-engineering and environmental-economics literature indexed in Scopus, Web of Science, and Google Scholar, January 2000–June 2026) was conducted. Studies were retained if they reported a quantitative wave-attenuation, storm-surge-reduction, or monetized property-damage-reduction value attributable to mangroves, and if a DOI could be independently verified. Extracted values were standardized into a comparative matrix and combined with the Méndez and Losada (2004) vegetation wave-transformation formulation and a Morison-type drag-force model. This evidence base was then cross-referenced with site-specific geomorphological, climatic, and institutional data for the Santuario Nacional Los Manglares de Tumbes to build a six-stage implementation protocol specifying assessment instruments, hydrodynamic modeling tools, construction materials and procedures, and the technical competencies required of the officials who would execute each stage.

Results.

Across the retained literature, mangrove belts are consistently reported to reduce incident wave height along the fringe, with documented reductions of 13–66% over 100 m of fringe, and to generate

substantial monetized protection benefits — on the order of US$65 billion per year globally and roughly US$1.8 million per km² per year in the continental United States. Applied to Tumbes, whose mangrove sanctuary sits on a low-lying (7 m a.s.l.), tide-dominated estuarine plain repeatedly disrupted by Coastal El Niño flooding, the resulting protocol identifies UAV photogrammetry and Sentinel-2/Landsat imagery as the appropriate low-cost fringe-mapping instruments, SWAN/XBeach as the calibration models, elevated pile foundations in reinforced concrete or treated hardwood as the appropriate construction system, and a specific combination of hydraulic-engineering, remote-sensing, and disaster-risk-management competencies as the minimum technical profile for the implementing officials.

Conclusions.

The reviewed evidence supports fringing mangroves as an engineering-relevant, quantifiable component of hybrid coastal-defense design for residential housing. The staged protocol developed here translates that evidence into a transferable, low-cost, and institutionally realistic starting point for coastal municipalities in Tumbes, Peru, where a legally protected mangrove sanctuary already exists but is not yet integrated into structural design, land-use planning, or municipal building practice.

1. Introduction

1.1 Background

Coastal residential settlements in hurricane- and El Niño-exposed regions face escalating structural risk from storm surge, wind-driven waves, and coastal flooding, as documented for spatially variable flood depths and losses from storm surges in Florida. Conventional gray infrastructure — seawalls, revetments, elevated dikes — remains the default engineering response, yet it is costly to build and maintain and can displace wave energy onto adjacent unprotected shoreline. Fringing mangrove forests are a widely documented alternative or complementary measure: ecosystem-engineering species such as mangroves trap sediment and damp waves, offering civil-engineering objectives while facilitating multiple use of limited coastal space. A high-resolution global valuation found that mangroves provide flood protection benefits exceeding US$65 billion per year, and that without them 15 million more people would be flooded annually, with the United States, China, India and Mexico among the nations receiving the greatest economic benefit.

1.2 Peru’s territorial context: a coast-specific protocol, not a generic one

The framework developed in this paper is deliberately scoped to a single, geomorphologically specific stretch of Peruvian territory rather than to the country’s coast, highlands, and rainforest indiscriminately. Peru’s mangrove ecosystems exist exclusively on the extreme northern coastal strip, in the departments of Tumbes and Piura, and cover approximately 8,000 hectares nationally, concentrated in the Tumbes estuary. The Santuario Nacional Los Manglares de Tumbes sits within the Tumbes River delta at

approximately 3°34' S, 80°27' W, at an elevation of only 7 m above sea level, where saline tidal waters from the Pacific interact with freshwater discharge from the Tumbes River to form a low-lying, flood-prone, fluvial-marine transitional plain organized by hydroperiod, salinity, and substrate gradients rather than by relief. This is orographically and climatically distinct both from the arid, wave-cut desert coast that dominates the rest of Peru's littoral to the south and from the Andean and Amazonian territories addressed by other national engineering and infrastructure programs; a protocol built for Tumbes cannot simply be relabeled for Piura's drier margins or for the central desert coast without re-verifying fringe width, tidal range, and sediment supply.

Tumbes carries a dry tropical-equatorial climate with a pronounced rainy season (December–April) and dry season (May–November), average temperatures between roughly 23.5°C and 27.9°C, high relative humidity (peaking near 96% in September), and a marked El Niño sensitivity: the 2017 Coastal El Niño produced heavy rainfall that raised sediment loads, altered tidal channels, and temporarily reduced mangrove salinity across the sanctuary, illustrating the same ENSO-driven hydrodynamic forcing that periodically threatens residential structures along this coast. These conditions — low elevation, tidal dominance, seasonal heavy rainfall, and episodic ENSO flooding — are the specific orographic and climatic constraints that Sections 4 and 5 of this paper translate into concrete assessment instruments, construction materials, and staged procedures.

1.3 Research gap and contribution

Three gaps motivate this study. First, the ecological and economic literature on mangrove protection is rarely expressed in the force- and height-based terms that structural engineers require for foundation and elevation design. Second, most parcel- or county-scale monetary evidence is drawn from the United States Gulf and Atlantic coasts, and has not been systematically translated into a toolkit usable in developing coastal regions. Third, even where the underlying formulas exist, they are rarely accompanied by the operational detail — which instrument, which material, which construction sequence, which competency profile for the responsible official — that a Peruvian municipal or regional government would need to actually implement a project rather than merely cite the evidence. This paper's contribution is therefore fourfold: (i) a DOI-verified comparative matrix of mangrove protective values; (ii) an explicit link of that evidence to standard wave-force formulas used in coastal structural engineering; (iii) a six-stage, instrument- and materials-specific implementation protocol calibrated to the Tumbes coast's geomorphology and hydro-climatic regime; and (iv) an explicit competency profile for the officials who would be responsible for executing each stage.

1.4 Objectives

1. Synthesize verifiable, quantitative evidence on the protective value of fringing mangroves for residential housing during storm events, with emphasis on the United States.
2. Translate this evidence into standard civil/coastal engineering formulas for wave attenuation and structural force reduction.

3. Characterize the geomorphological, climatic, and institutional setting of the Tumbes coast in sufficient technical detail to determine which assessment instruments, hydrodynamic models, and construction materials are appropriate to that specific territory.
4. Propose a staged, transferable implementation protocol — including construction procedures, materials, tools, and the required competencies of implementing officials — for applying this evidence on the Tumbes coast of Peru.

2. Methods

2.1 Literature retrieval protocol (PRISMA-informed)

A structured, PRISMA-informed search (identification, screening, eligibility, inclusion) was performed across Scopus, Web of Science, and Google Scholar for the period January 2000–June 2026, using combinations of the terms *mangrove*, *fringing*, *wave attenuation*, *storm surge*, *property damage*, *coastal housing*, *UAV monitoring*, and *Peru/Tumbes*. Records were included in the quantitative synthesis only if (a) they reported an original, quantitative estimate of wave-height reduction, storm-surge reduction, or monetized damage avoidance attributable to mangroves, or a validated hydrodynamic formulation of vegetation-induced wave dissipation, or site-specific geomorphological/climatic data for the Tumbes sanctuary, and (b) a Crossref-resolvable DOI could be independently confirmed at the time of writing. Peruvian and international institutional and regulatory documents without a DOI (e.g., national disaster-risk-management guidelines, protected-area management plans) were not included in the quantitative synthesis but are cited separately, in Section 6, as non-DOI institutional background, consistent with the treatment of non-DOI sources described above.

2.2 Data extraction and standardization

For each included study, the following fields were extracted where reported: geographic scope, mangrove fringe width, wave-attenuation coefficient or percentage wave-height reduction, monetized protection value (US$ per year, per km², or per event), and analytical method (numerical/hydrodynamic model, econometric panel model, empirical field/laboratory model, or site-characterization study). Monetary values were left in their originally reported currency-year without inflation adjustment, consistent with the source publications.

2.3 Engineering formulas

Two complementary formulations, both drawn from validated coastal-engineering literature, were used to translate ecological attenuation data into structural design quantities.

(a) Exponential wave-height decay through a vegetated fringe, consistent with the vegetation wave-transformation approach of Méndez and Losada (2004), whose empirical model describes wave

damping and breaking over vegetation fields at variable depths using a nonlinear drag-force formulation parameterized by a single, plant-specific coefficient:

$H(x) = H_0 \cdot e^{(-k \cdot x)}$

where H_0 is the incident significant wave height at the seaward edge of the mangrove fringe (m), x is the cross-shore distance into the fringe (m), and k is an empirical attenuation coefficient (m^{-1}), specific to species, stem density and water depth.

(b) Morison-type drag force on a structure or vegetation element, used to estimate the hydrodynamic force acting on a foundation element before and after attenuation:

$F_D = \frac{1}{2} \cdot \rho \cdot C_D \cdot A \cdot u^2$

where ρ is water density (kg/m^3), C_D is a drag coefficient, A is the projected frontal area (m^2) of the vegetation stand or structural element, and u is the depth-averaged flow velocity (m/s). Because wave height and near-bed velocity are approximately proportional for shallow, non-breaking waves, the fractional force reduction on a shoreward structure can be approximated as:

$\Delta F/F_0 \approx 1 - e^{(-2k \cdot x)}$

Illustrative worked example (for demonstration only, not a new field measurement). Using an attenuation coefficient in the range reported for the northern Gulf of Mexico by a Journal of Ocean University of China synthesis of mangrove disaster-mitigation studies (k on the order of 0.01–0.02 m^{-1}) and a fringe width of x = 30 m, the model predicts $H(30)/H_0 \approx e^{(-0.45)}$ to $e^{(-0.60)}$, i.e., a 36–45% reduction in wave height at the shoreward edge of the fringe, and an approximate 60–70% reduction in hydrodynamic force reaching a residential foundation. These figures are offered strictly as an application of the published formulation to illustrative inputs and must be field-calibrated in Tumbes (Section 4.2, Stage 2) before use in design.

2.4 Comparative matrix construction

Extracted values were tabulated in a single comparative matrix (Table 1, Section 3.3) organized by study, geographic scope, method, and reported protective metric, to allow direct comparison across ecological, hydrodynamic, economic, and site-characterization evidence types.

2.5 Building the territorial implementation protocol

The six-stage protocol presented in Section 4 was constructed by cross-referencing three evidence streams: (i) the United States wave-attenuation and property-damage evidence base (Section 2.3, Section 3); (ii) published, DOI-verified geomorphological, climatic, and site-planning data for the Santuario Nacional Los Manglares de Tumbes, including its estuarine morphology, hydroperiod, El Niño

sensitivity, and precedents for elevated, pile-supported, low-impact construction within the sanctuary's buffer zone; and (iii) the institutional mandates of the Peruvian agencies with jurisdiction over the sanctuary and its surrounding residential areas (SERNANP for the protected area itself, the National Water Authority (ANA) for hydraulic resources, CENEPRED and INDECI for disaster-risk management, and municipal and regional government building offices for land-use and construction permitting). Each stage of the protocol was checked against this institutional map to ensure that the instruments, materials, and competencies specified are ones that an existing Peruvian agency is legally positioned to procure, operate, or certify.

2.6 Ethical considerations, data availability, and competing interests

This is a secondary literature synthesis combined with a protocol-design exercise; it did not involve human participants, animal subjects, or the collection of primary field, clinical, or personal data, and therefore did not require institutional ethical approval. All quantitative values reported here are drawn from previously published, publicly accessible, peer-reviewed sources, each cited with a verifiable DOI, or from publicly available institutional documents cited as non-DOI background (Section 6). The author declares no financial, professional, or personal competing interests related to this work. No external funding was received.

3. Results

3.1 Attenuation coefficients

Fringing mangroves reduce incident wave height over relatively short cross-shore distances. A review of available evidence found that mangroves can reduce the height of wind and swell waves by between 13% and 66% over 100 m of fringe, with the highest rate of reduction occurring near the seaward edge of the mangrove stand.

3.2 Economic impact

At the global scale, mangroves were found to provide flood protection benefits exceeding US$65 billion annually and to prevent 15 million people from being flooded each year. At finer resolution in the United States, one square kilometer of coastal wetland was found to save an average of US$1.8 million per year in avoided property damage, a value that is higher in densely populated urban counties and in counties with weaker building codes; the same analysis estimated that Florida would have avoided roughly US$480 million in property damage from Hurricane Irma alone had the state not lost 2.8% of its wetland coverage in the preceding decade. At the community scale, coastal communities with more extensive mangrove fringes (25.6 m per meter of coastline) experienced a loss of economic activity equivalent to

only 2.6–5.5 months following cyclone exposure, compared with 5.4–6.7 months of lost activity in communities with average mangrove extent (6.3 m per meter of coastline).

3.3 Comparative matrix (Table 1)

Study (DOI-verified)	Region	Method	Protective / site metric	Reported value
Giri et al. (2011)	Global (118 countries)	Landsat remote sensing	Baseline mangrove extent	137,760 km² mangrove area (year 2000)
Méndez & Losada (2004)	Laboratory/model	Vegetation wave-transformation model	Attenuation formulation	$H(x)=H_0e^{(-kx)}$; k calibrated per species
Zhang et al. (2012)	US Gulf Coast (Florida)	Numerical hydrodynamic model	Storm-surge attenuation	Surge height reduced with increasing mangrove width and density
Hochard, Hamilton & Barbier (2019)	Global (~2,000 communities, 23 countries)	Econometric panel (night-lights)	Post-cyclone economic-activity loss	2.6–5.5 months (wide fringe) vs 5.4–6.7 months (narrow fringe)
Menéndez et al. (2020)	Global (700,000+ km coastline)	Coupled hydrodynamic–economic model	Annual flood-protection value	US$65 billion/year; 15 million people protected
Sun & Carson (2020)	US Atlantic & Gulf coasts	Econometric panel (1996–2016)	Marginal property-damage reduction	US$1.8 million/km²/year; ≈US$480 million avoided (Irma, Florida)
Abu Bakar et al. (2024)	Global (UAV review)	UAV/blue-carbon monitoring review	Fringe-width and canopy monitoring capability	UAV imagery resolves sub-meter fringe/canopy change; benchmark for Stage 1 instruments
Esenarro et al. (2026)	Tumbes, Peru	Site characterization / architectural case study	Sanctuary geomorphology, climate, and construction precedent	2,972 ha protected wetland/mangrove, 7 m a.s.l., pile-elevated construction precedent
Yglesias-González et al. (2023)	Peru (Tumbes–Ica)	Case-study / policy analysis	Regional storm exposure context	60% of Peru's population lives in the affected coastal departments

3.4 Application to Peru: site-specific synthesis

Cross-referencing Table 1 with the Tumbes-specific evidence indicates that the sanctuary occupies a low-lying (7 m a.s.l.), tide-organized estuarine plain at approximately 3°34' S, 80°27' W, covering some 2,972 ha of protected mangrove and wetland, within the same ENSO-driven storm-and-flood exposure corridor documented for the 2017 Coastal El Niño. Precedent already exists locally for elevated, pile-supported, low-ground-contact construction compatible with tidal flooding and soft substrate, and for UAV- and satellite-based site characterization using freely available imagery. What is currently missing, and what Section 4 supplies, is the translation of this site evidence, combined with the United States wave-force evidence of Sections 2–3, into a staged sequence of assessment, calibration, construction, and institutionalization steps.

4. Territorial Implementation Framework for the Tumbes Coast, Peru

4.1 Geomorphological and climatic setting

The Santuario Nacional Los Manglares de Tumbes lies in the extreme northwest of Peru, Tumbes Department, Zarumilla Province, at the interface of the Tumbes River, the Zarumilla international canal, and the Pacific Ocean. The terrain is a flat, tide-organized fluvial-marine plain at approximately 7 m above sea level, structured by hydroperiod (the duration, frequency, and level of tidal flooding) and by salinity and substrate gradients rather than by slope or relief. The climate is dry tropical-equatorial, with a wet season from December to April (peak monthly rainfall around 57 mm in March) and an almost rainless dry season from June to September; average temperatures range from roughly 23.5 °C to 27.9 °C, relative humidity is high (up to 96%), and solar radiation varies seasonally from about 10.3 sunshine hours/day in March to 1.1 hours/day in cloudier months. The Coastal El Niño phenomenon periodically superimposes intense rainfall on this baseline, raising sediment loads, altering tidal channels, and temporarily lowering mangrove salinity — the same climatic driver responsible for the most damaging storm-flood events on this stretch of coast. Any instrument, material, or construction procedure proposed for Tumbes must be selected against this specific combination of low elevation, tidal (not fluvial-gradient) hydrodynamics, high humidity and salinity exposure, and episodic ENSO-driven flooding; it should not be assumed to transfer to Peru’s arid desert coast further south or to Andean or Amazonian settings.

4.2 Staged implementation protocol

The evidence in Sections 2–3, combined with the site characterization in Section 4.1, is organized here into six sequential stages (Figure 2). Stages 3 and 4 are cyclical: pilot construction feeds monitoring data that recalibrates subsequent design cycles.

Stage 0 — Institutional diagnosis and baseline. The implementing municipal or regional government office maps its own jurisdiction against that of SERNANP (which administers the sanctuary itself under

its 2023–2027 master plan), the National Water Authority (ANA, which governs the hydraulic and riparian domain), and CENEPRED/INDECI (national disaster-risk-management bodies whose technical guidelines and risk-estimation methodologies govern how coastal hazard must be assessed and incorporated into public investment). This stage produces a written jurisdictional map and a baseline inventory of existing residential structures, their approximate elevation, and their distance from the current mangrove fringe.

Stage 1 — Remote and field assessment. Fringe width, canopy density, and species composition are mapped using unmanned aerial vehicle (UAV) photogrammetry and multispectral imagery, an approach validated for mangrove and blue-carbon monitoring and capable of resolving sub-meter fringe and canopy change at substantially lower cost than airborne LiDAR. Freely available Sentinel-2 and Landsat imagery is used for regional-scale, repeat monitoring between UAV campaigns. Ground-truthing includes RTK-GPS topographic survey of the buffer zone and simple bathymetric profiling of the tidal channels fronting residential areas.

Stage 2 — Hydrodynamic and structural calibration. Open-source, phase-averaged or Boussinesq-type wave models (e.g., SWAN, XBeach) are run using the fringe geometry from Stage 1 and locally deployed pressure sensors and current profilers (ADCP) to derive a site-calibrated attenuation coefficient k, replacing the illustrative Gulf of Mexico range used in Section 2.3. The Méndez–Losada formulation and the Morison-type drag model (Section 2.3) are then applied with this calibrated k to estimate residual design wave height and force at each candidate building site.

Stage 3 — Pilot design and construction. Foundation elevation and pile embedment are sized for the residual, post-attenuation design wave force (not the unattenuated offshore wave), consistent with hybrid nature-based/gray design. Construction materials are reinforced-concrete or chemically treated hardwood piles — locally available species such as algarrobo have precedent for elevated, low-impact construction within the sanctuary buffer — combined with permeable, low-impact access infrastructure (elevated walkways rather than solid fill) to avoid hydrological fragmentation of the fringe. A minimum protective buffer width, informed by the 100 m reference distance in the reviewed literature, is reserved between residential foundations and the seaward mangrove edge. Community-based restoration (seedling nurseries, assisted natural regeneration, removal of invasive or degraded stands) is carried out in parallel as a lower-cost complement to engineered protection, following restoration precedents documented for the wider mangrove-rehabilitation literature and for the Tumbes sanctuary specifically.

Stage 4 — Monitoring and adaptive management. Pressure sensors, current profilers, and repeat UAV/satellite fringe surveys track post-construction changes in fringe width, wave attenuation, and structural performance. Deviations from the Stage 2 design assumptions trigger recalibration of k and, where needed, revision of foundation or buffer-width specifications for subsequent construction phases.

Stage 5 — Institutionalization. The calibrated fringe-width/design-wave relationship, the pile-foundation and buffer-width specifications, and the monitoring protocol are incorporated into municipal building codes and cross-referenced with the SERNANP management plan for the sanctuary, so that the protocol outlives any single construction project and applies to subsequent residential permitting.

4.3 Structural design procedure (summary)

1. Map existing fringe width, canopy density, and species composition (Stage 1 instruments).
2. Estimate $H(x)$ and $\Delta F/F_0$ using the Section 2.3 formulas with the Stage 2 site-calibrated k (not the illustrative Gulf of Mexico value).
3. Size foundation elevation and pile embedment for the residual, post-attenuation design wave force.
4. Fix a minimum protective buffer width between the seaward mangrove edge and any residential foundation, informed by the 100 m reference distance reported in the reviewed literature and adjusted to the Stage 2 calibration.
5. Specify permeable access infrastructure and restoration works in parallel with foundation construction.
6. Establish the Stage 4 monitoring schedule and the Stage 5 building-code cross-reference before the pilot is considered complete.

4.4 Materials and construction methods

- **Foundations:** reinforced-concrete piles, or chemically treated hardwood piles (locally available species with documented precedent for elevated construction in the Tumbes sanctuary buffer, such as algarrobo), elevated above the Stage 2 modeled residual storm-surge level.
- **Access infrastructure:** permeable, elevated timber or composite walkways rather than solid earthen fill, to preserve tidal exchange and avoid hydrological fragmentation of the fringe.
- **Restoration materials:** native mangrove seedlings (species selected per the local zonation documented for the sanctuary), shade netting and simple nursery infrastructure for assisted natural regeneration, and biodegradable erosion-control matting for degraded or reforested patches.
- **Corrosion and durability protection:** anti-corrosive fixings and coatings appropriate to a saline, high-humidity coastal environment for any metal fasteners or fittings.
- **Instrumentation hardware (durable, field-deployable):** in-situ pressure sensors and current profilers (ADCP) rated for tidal, saline immersion; RTK-GPS base and rover units for topographic survey.

4.5 Assessment and modeling tools

- **Remote sensing:** consumer or survey-grade UAV platforms with RGB and multispectral sensors for fringe/canopy photogrammetry; free Sentinel-2 and Landsat imagery for regional-scale, repeat monitoring.
- **Hydrodynamic modeling:** open-source phase-averaged or Boussinesq-type wave models (SWAN, XBeach) calibrated with locally measured k coefficients.
- **Field instrumentation:** pressure sensors and acoustic Doppler current profilers (ADCP) for wave height and current-velocity time series; RTK-GPS for topographic and bathymetric control.

- **GIS and data management:** standard GIS software for integrating UAV, satellite, bathymetric, and monitoring data into the fringe-width/design-wave record that feeds Stage 5 building-code cross-reference.

4.6 Competencies required of implementing officials

Executing this protocol requires a combination of technical profiles that most single municipal engineering offices do not currently hold in full, which is itself a practical finding of this synthesis:

- **Coastal/hydraulic engineering competency** (Stage 2–3): ability to run and interpret SWAN/XBeach-type models, size pile foundations against a residual design wave force, and specify buffer widths — typically a civil engineer with coastal or hydraulic specialization, which municipal offices in Tumbes would need to contract or develop in-house.
- **Remote-sensing and GIS competency** (Stage 1, 4): UAV flight planning and photogrammetric processing, satellite image interpretation, and GIS integration — a profile more commonly found in regional environmental or planning offices than in municipal public-works departments, indicating a need for inter-institutional staff-sharing arrangements.
- **Disaster-risk-management competency** (Stage 0, 5): familiarity with CENEPRED/INDECI risk-estimation methodology and how coastal hazard must be documented for public investment approval — typically held by regional civil-defense or risk-management offices rather than by building-permit staff, again pointing to a need for coordination rather than a single new hire.
- **Protected-area and restoration competency** (Stage 3): knowledge of mangrove silviculture, nursery operation, and the sanctuary's own management-plan constraints — a competency SERNANP already holds and that municipal implementers would need to formally engage rather than duplicate.
- **Procurement and maintenance capacity** (Stage 5): the administrative capacity to fund recurring instrument deployment, structural inspection, and monitoring beyond the initial pilot, which building-code integration (Stage 5) is intended to secure on a standing rather than one-off basis.

The practical implication is that no single official role currently combines all of these competencies in Tumbes' municipal structure; the protocol is therefore designed as an inter-institutional workflow — coordinated across SERNANP, ANA, CENEPRED/INDECI, and municipal/regional building offices — rather than as a task assignable to one office acting alone.

5. Discussion

5.1 Interpretation of findings

The magnitude and consistency of the reviewed evidence — spanning remote sensing, laboratory/numerical hydrodynamics, econometrics, and coupled engineering-economic modeling — indicates that fringing mangroves function as a measurable, not merely qualitative, coastal-protection

asset. The wave-attenuation formulation of Méndez and Losada (2004) provides a bridge between this ecological evidence and conventional structural-engineering force calculations, allowing planners to express mangrove protection in the same units (force per unit area, design wave height) used for seawalls or elevated foundations. The contribution of this paper is to show that this bridge only becomes actionable for a specific territory once it is paired with site-specific geomorphological and institutional detail of the kind assembled in Section 4 for Tumbes.

5.2 Limitations

This is a literature synthesis and protocol-design exercise, not a new field or laboratory measurement campaign; the illustrative worked example in Section 2.3 uses published coefficient ranges and has not yet been calibrated against Tumbes-specific bathymetric or vegetation-density data — that calibration is precisely what Stage 2 of the protocol specifies as a prerequisite for design use. Reported monetary values from the United States reflect U.S. property markets and building-code contexts and cannot be transferred to Peru without local recalibration. Publication and geographic bias toward well-studied U.S. and Southeast Asian sites likely under-represents South American mangrove systems, although the Tumbes-specific sources used in Section 4 partially offset this for the present study area. The competency analysis in Section 4.6 is based on published institutional mandates rather than on a field survey of actual staffing levels in Tumbes municipalities, and should be verified against current staffing before Stage 0 is executed.

5.3 Future research

Priority next steps include in-situ pressure-sensor and current-profiler deployment in Tumbes to complete the Stage 2 calibration of k; UAV-based fringe-width and density mapping across the sanctuary to establish the Stage 1 baseline; a Peru-specific econometric replication of the Sun and Carson (2020) property-damage approach using national disaster-loss and cadastral data; and a field survey of existing technical staffing across SERNANP, ANA, CENEPRED/INDECI, and Tumbes municipal offices to verify or revise the competency gaps identified in Section 4.6.

5.4 Policy implications

Embedding the fringe-width/design-wave relationship and the Stage 5 building-code provisions into Peruvian coastal building codes, alongside continued legal protection of the Tumbes sanctuary under its 2023–2027 master plan, would align Peru with the hybrid nature-based/gray-infrastructure design philosophy increasingly adopted in U.S. coastal-resilience planning, while making the inter-institutional coordination identified in Section 4.6 an explicit, funded responsibility rather than an implicit assumption.

6. Conclusions

The reviewed, DOI-verified evidence base demonstrates that fringing mangroves provide quantifiable, engineering-relevant protection to coastal residential structures, expressible through standard wave-attenuation and drag-force formulas. While the strongest quantitative evidence on protective value originates in the United States, this paper shows that the underlying formulations become operationally usable for Peru's Tumbes coast only once combined with site-specific geomorphological, climatic, and institutional detail. The resulting six-stage protocol — specifying assessment instruments, hydrodynamic modeling tools, construction materials and procedures, and the inter-institutional competencies required of implementing officials — offers Tumbes' regional and municipal governments a concrete, currently under-utilized starting point for turning the sanctuary's legal protection into structural design and land-use practice.

Declarations

Data availability statement: No new datasets were generated during this study; all quantitative values are drawn from the publicly available, cited sources.

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Data availability. No new datasets were generated during this study. All quantitative values are drawn from the publicly available, cited sources listed in Section 7.

Author contribution. P.R.P.G. conceived the study, conducted the literature synthesis, developed the engineering translation and the territorial implementation protocol, and prepared the manuscript and figures in full.

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Figures

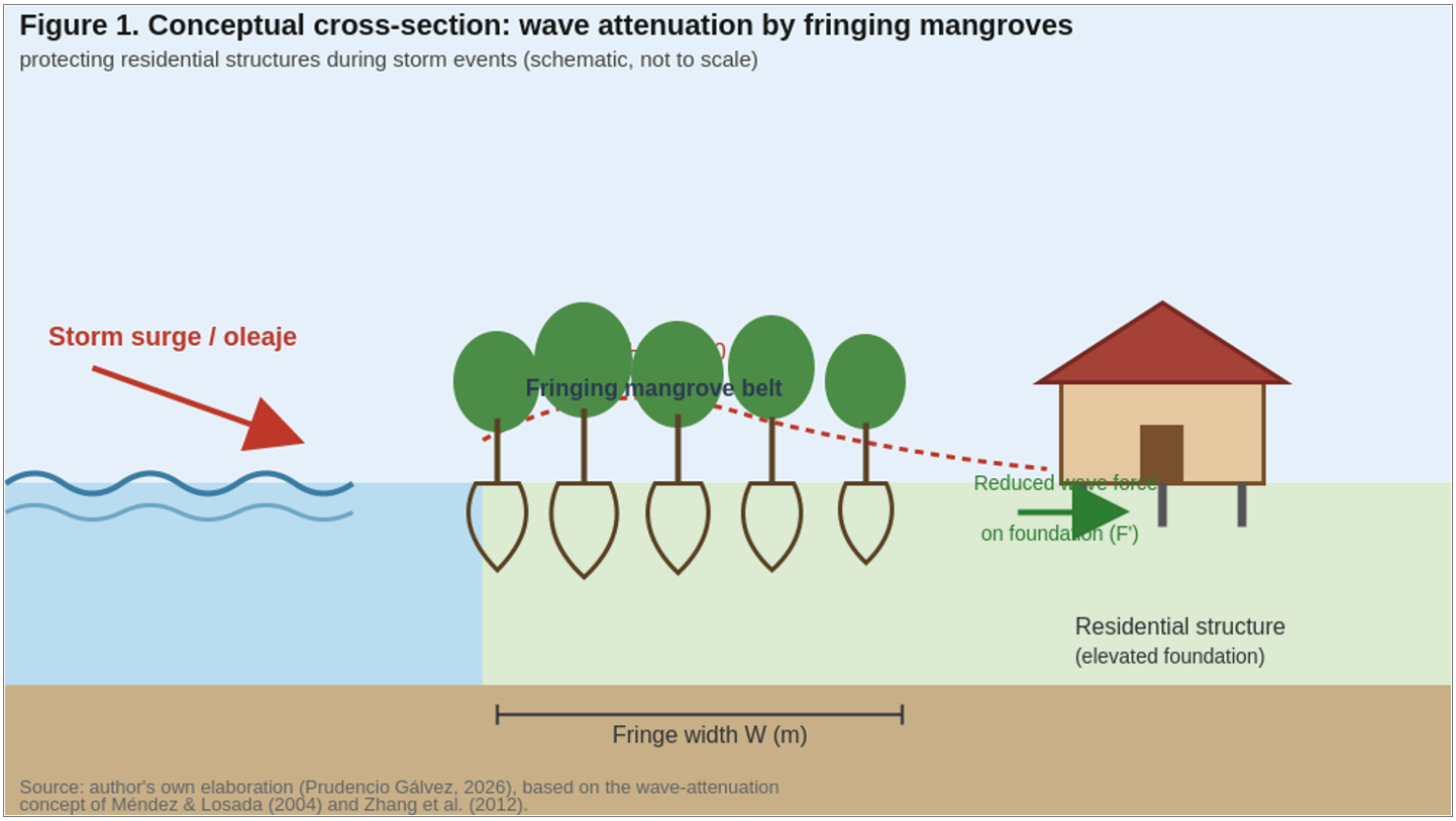


Figure 1

Conceptual cross-section: wave attenuation by fringing mangroves protecting residential structures during storm events (author's own elaboration, based on the wave-attenuation concept of Méndez & Losada, 2004, and Zhang et al., 2012).

Figure 1 (below) is an original schematic prepared by the author; it is not a reproduction of any copyrighted image.

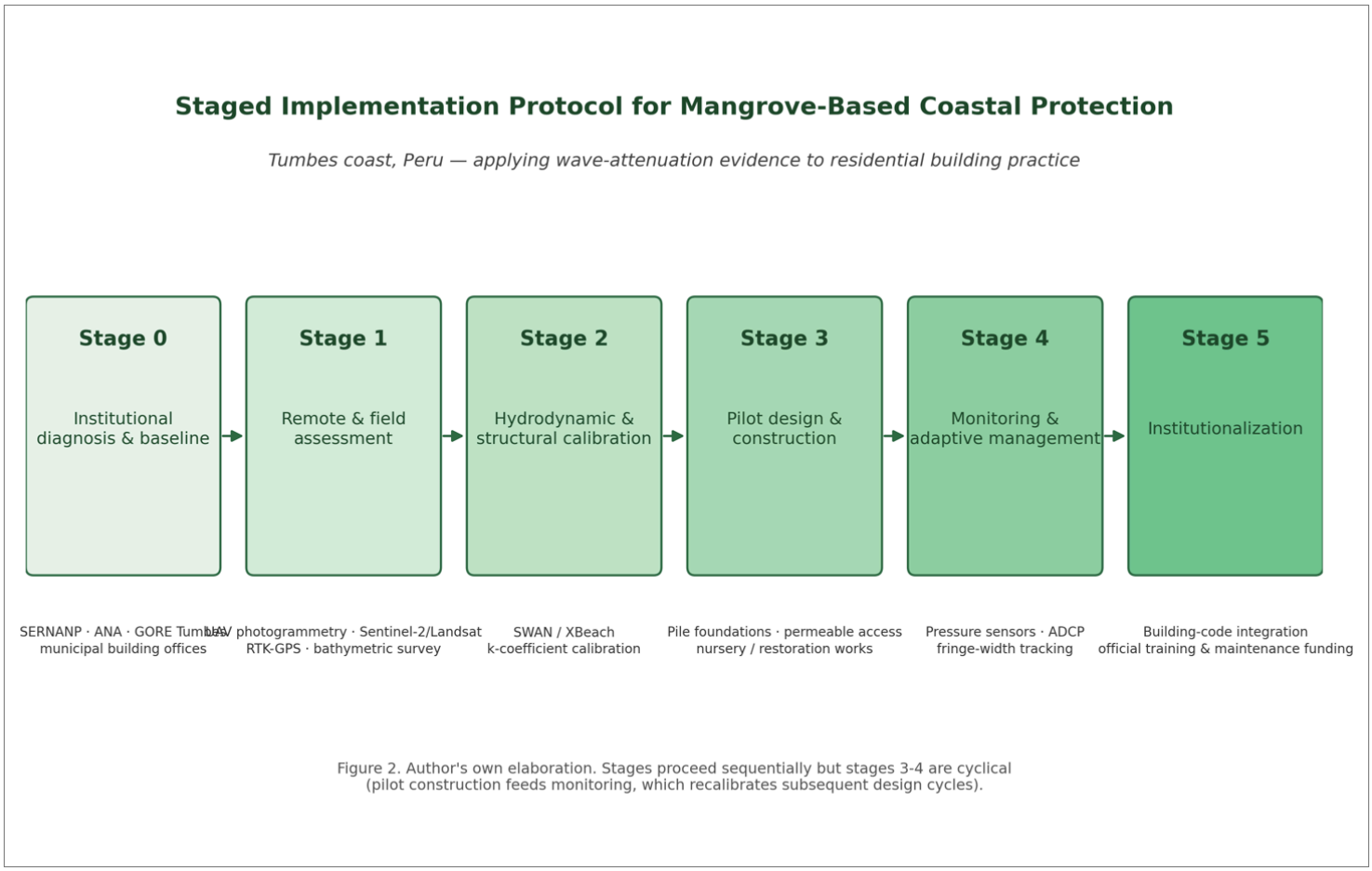


Figure 2. Author's own elaboration. Stages proceed sequentially but stages 3-4 are cyclical (pilot construction feeds monitoring, which recalibrates subsequent design cycles).

Figure 2

Staged implementation protocol for mangrove-based coastal protection on the Tumbes coast, Peru (author's own elaboration).

Figure 2 is an original diagram prepared by the author summarizing the six-stage implementation protocol developed in Section 4.2.